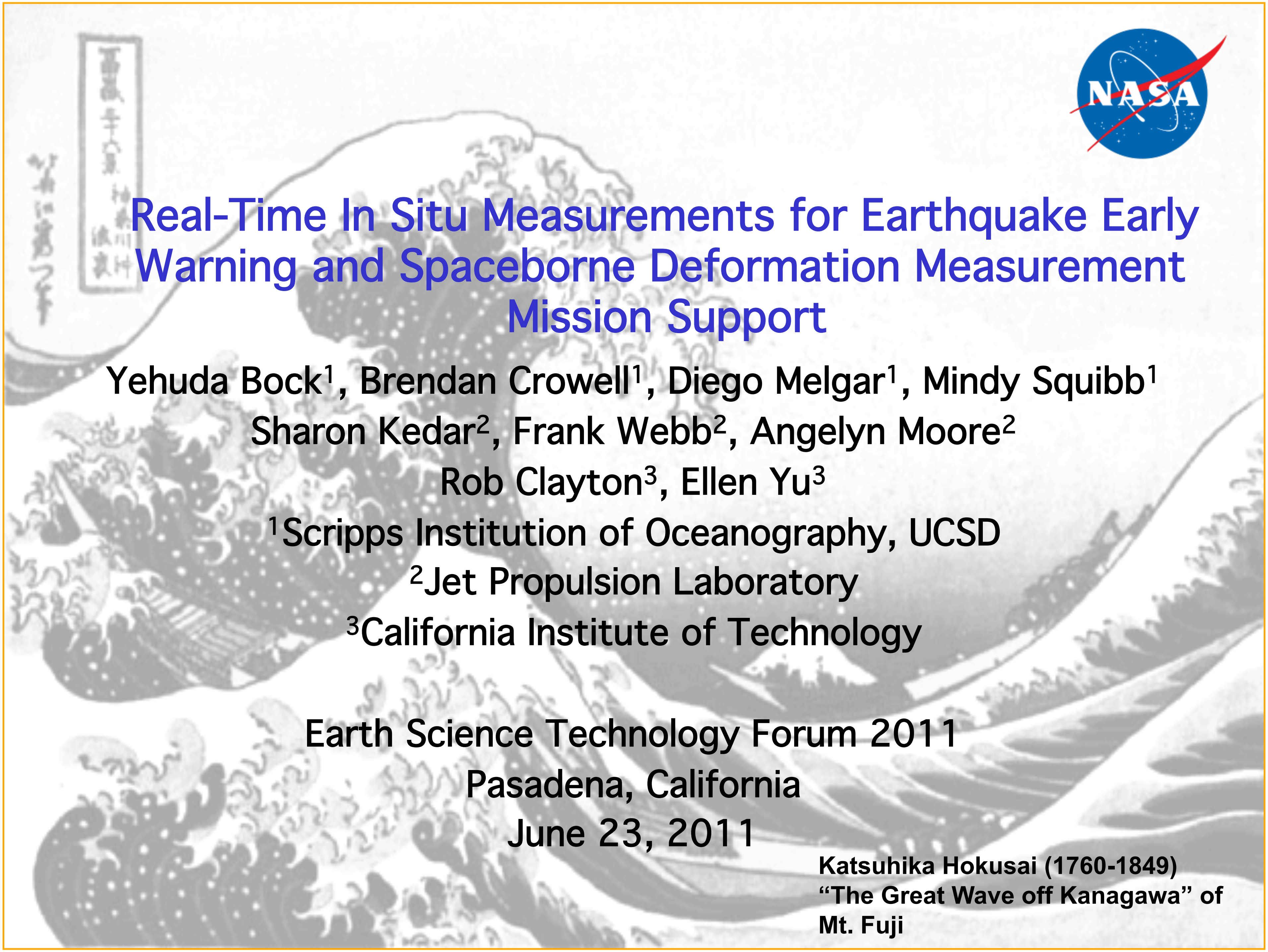
Real-Time In Situ Measurements for Earthquake Early Warning and Spaceborne Deformation Measurement Mission Support

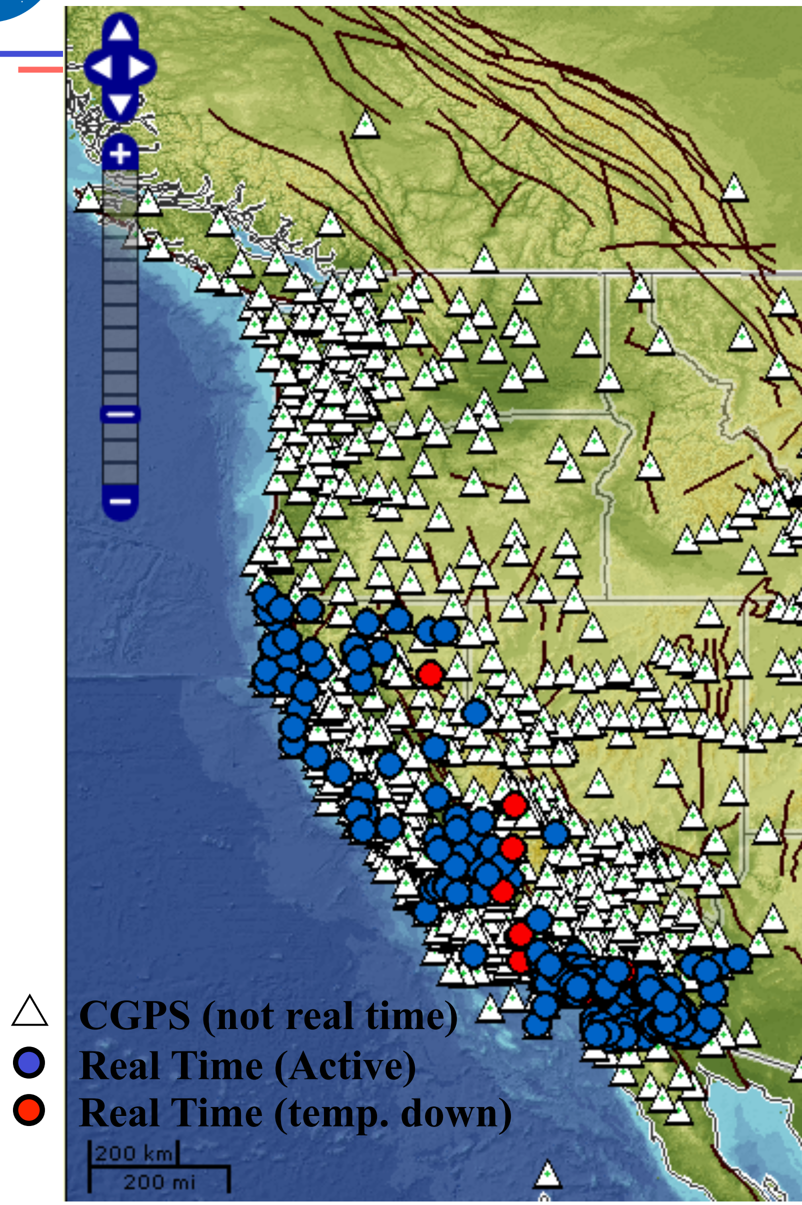
Yehuda Bock[1], Brendan Crowell[1], Diego Melgar[1], Mindy Squibb[1]
Sharon Kedar[2], Frank Webb[2], Angelyn Moore[2]
Rob Clayton[3], Ellen Yu[3]
[1]Scripps Institution of Oceanography, UCSD
[2]Jet Propulsion Laboratory
[3]California Institute of Technology

Earth Science Technology Forum 2011
Pasadena, California
June 23, 2011



Katsuhika Hokusai (1760-1849)
“The Great Wave off Kanagawa” of Mt. Fuji

In Situ GPS Networks for Monitoring Crustal Deformation



NASA has a long history of supporting ground-based global geodetic networks.

First continuous GPS (CGPS) network established in 1991 in S. California by JPL and SIO researchers with <u>NASA funding</u>; Evolved into the 250-station SCIGN project. Today there are ~1400 GPS stations in the Western U.S.

First real-time high-rate GPS network established in 2002 in S. California, also <u>funded by NASA</u>. Evolved into the nearly 200-station CRTN project. Today there are about 600 such stations in the Western U.S.

"Real-time" (to Server): < 0.5 s
"High-rate": 1 Hz

Overall Goal and Primary NASA Mission

To provide the most accurate and timely early warning information on global geological hazards to first responders, scientists, mission planners and policy makers

The primary mission of focus is NASA's Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission (Future of this mission???)

Objectives of AIST Project

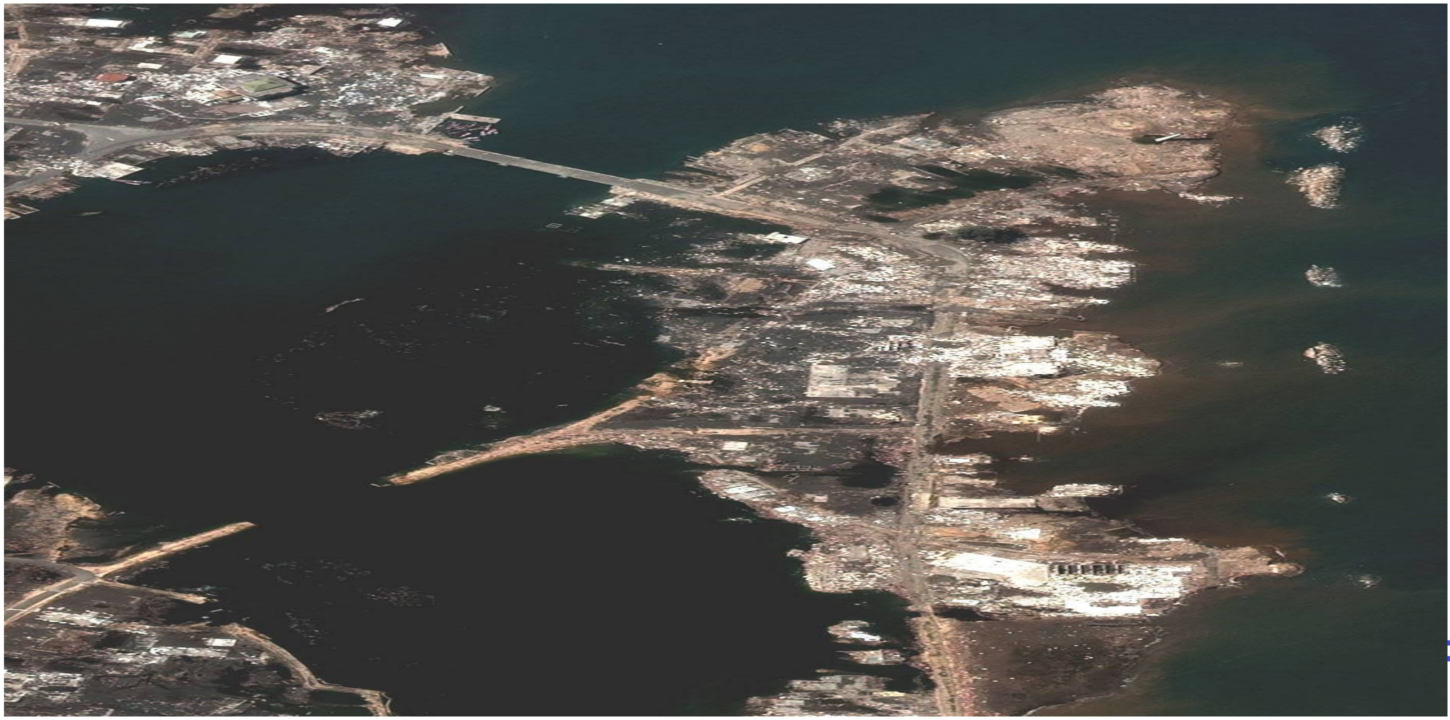
- Develop a publicly available real-time ground deformation data system fusing two in situ network data sources: low latency (<1 s) high-rate (1 Hz or greater) continuous GPS & traditional seismic data (accelerometers)

- Enable rapid access to total displacement waveforms, replay capability, and modeling of significant events related to global geological hazards

- Enable rapid detection and preliminary modeling of signals of interest by the dense ground networks, which will help mission planners exploit less-frequent but higher resolution InSAR observations

- Use GPS data products to calibrate InSAR measurements for atmospheric & orbital errors, significantly increasing the accuracy of interferograms

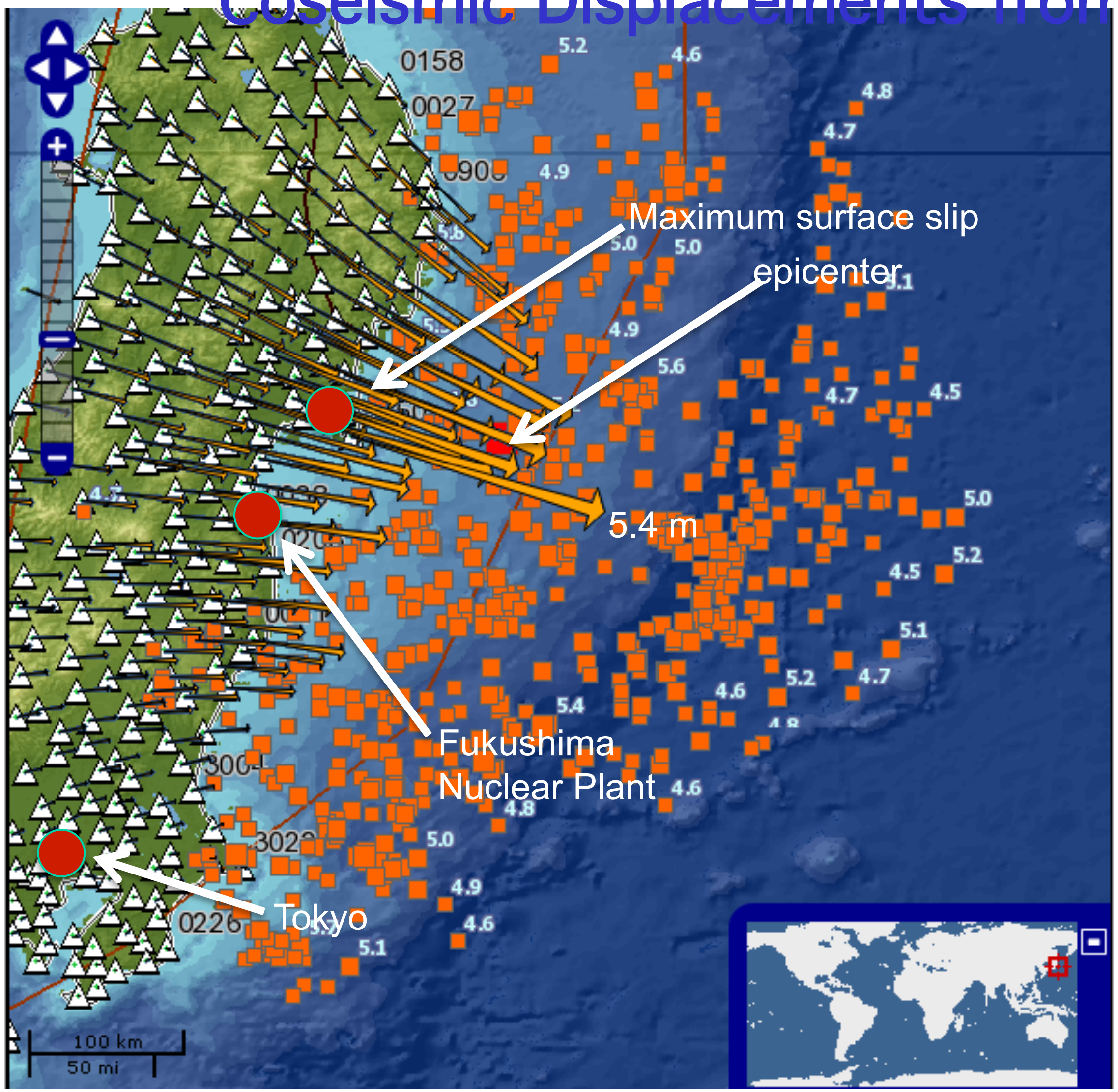
Banda Aceh, Sumatra before 2004 Mw 9.2 Great Sumatra Earthquake & tsunami



Banda Aceh after disaster: 200,000 casualties in Indonesia alone

ESTO
Earth Science Technology Office

March 11, 2011 Mw 9.0 Tohoku-oki Earthquake:
Coseismic Displacements from 30 s GPS data



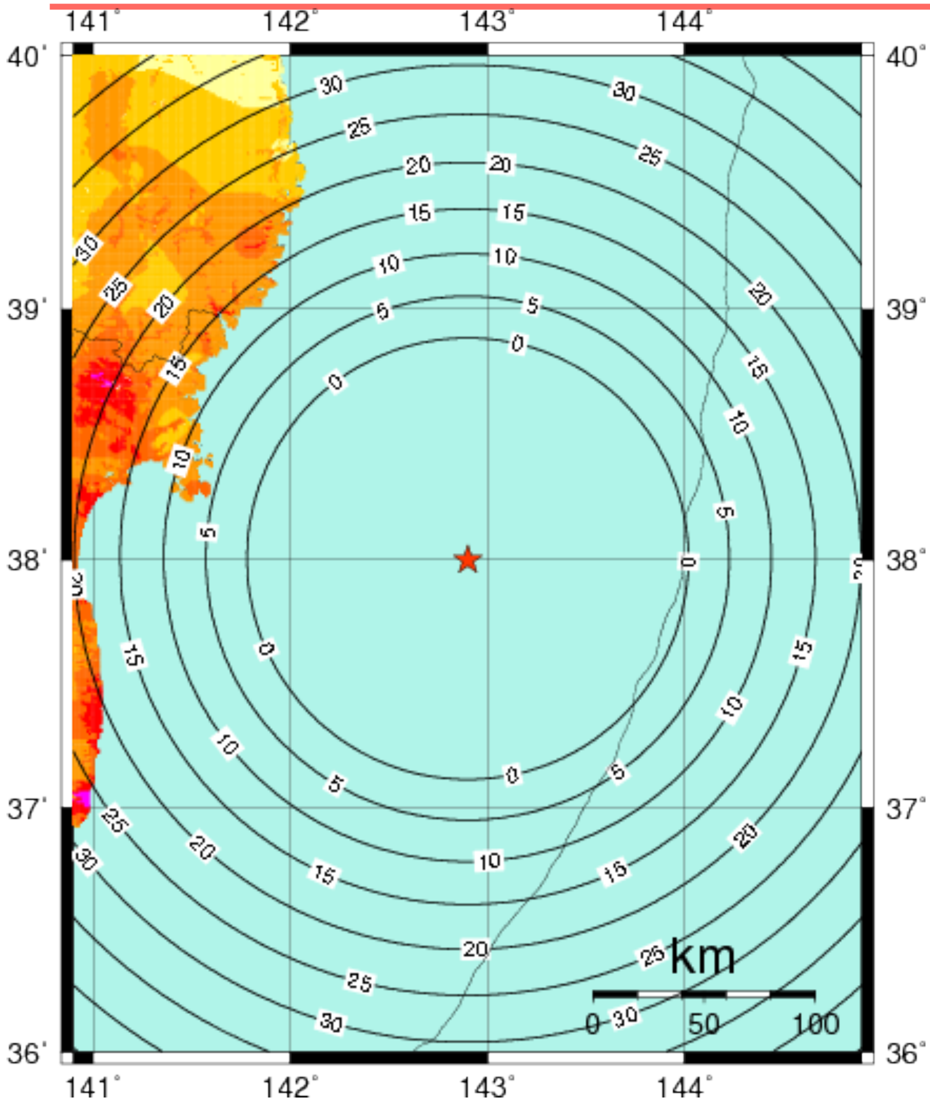
Shown in figure are coseismic displacements in the epicentral region computed from Japan's 1200+ station CGPS network (GEONET) by ARIA group at Caltech/JPL (courtesy of Susan Owen, JPL). Maximum surface displacement on land was 5.24 meters at GEONET station 0550 on coast.

Basic Elements of Earthquake Early Warning (EEW)

- **Radio waves travel faster than seismic waves**
- **P (primary) wave carries <u>information</u>**
- **S (secondary) wave carries <u>energy</u>**

(from a talk by Hiroo Kanamori at EEW Summit at UC Berkeley in April, 2011)

EEW – 2011 Mw 9.0 Tohoku-oki Earthquake



Amount of seconds until first warning was issued for 2011 Mw 9.0 Tohoku-oki earthquake. The contours show seconds until the S-wave arrival. The region within the 0 s contour is the blind zone where no warning is available. This illustration shows that the warning was issued before the S-wave reached the coastline.

(Based on JMA report summarizing the earthquake and tsunami warnings)

http://seismo.berkeley.edu/~rallen/research/WarningsInJapan/

Surviving Sendai (the closest city to 2011 Mw 9.0 Tohoku-oki earthquake) - a first person account:

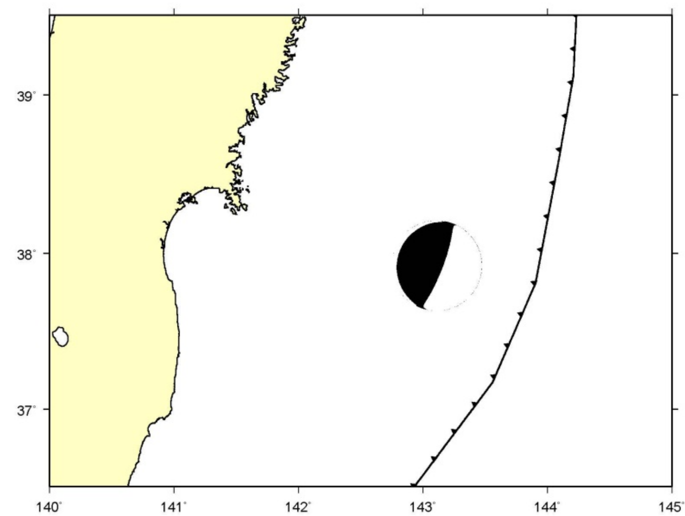
"Our meeting was being held on the second floor of an office building near Sendai Station. Suddenly, during our discussions, our mobile phones began to ring with the distinctive earthquake alarm. ... This gave us a window of a few seconds to prepare before the shaking began. My business partner and I took shelter on the floor beneath a steel door frame and waited for the shaking to begin. Although the building we were in was fairly new, the shaking was strong enough that we were not able to stand. Dust and debris from the ceiling began to fall like snow and large cracks appeared in the walls."

The account of Basil Tonks, Simcoe, March 15, 2011

http://seismo.berkeley.edu/~rallen/research/WarningsInJapan/

The first 60 minutes after the Tohoku-oki earthquake

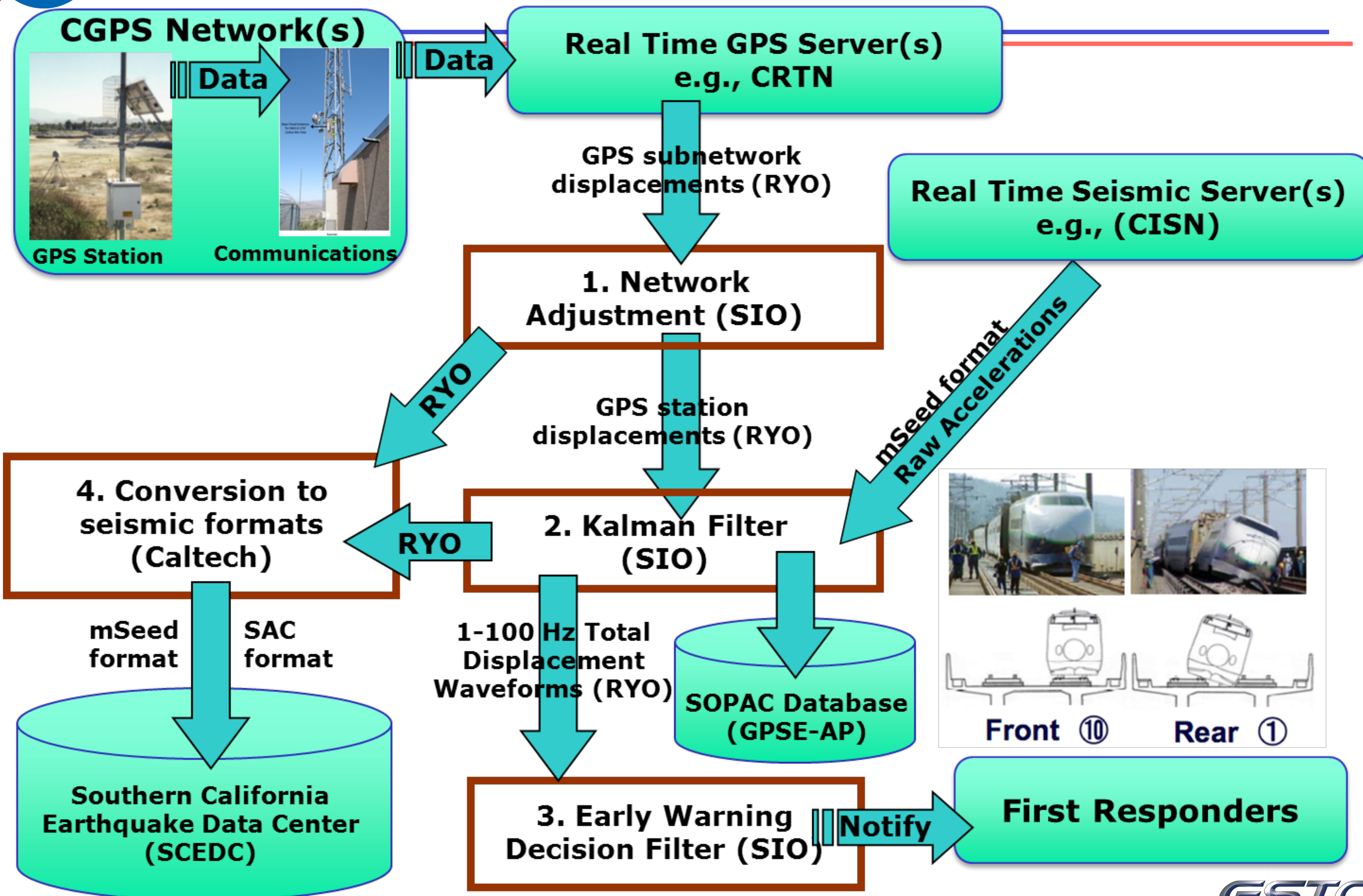
Time after OT	Source and method	Magnitude
3 min	JMA initial	6.8
5 min	PTWC Mwp	7.3
10-20 min	PTWC, ATWC, JMA	7.9
20 min	NEIC W phase	9.0
22min	PTWC W phase	8.8
27 min	USGS Research CMT	8.9
30 min	PTWC W phase	8.8
45 min	Strasbourg W phase	8.8
62 min	NEIC W phase	8.9



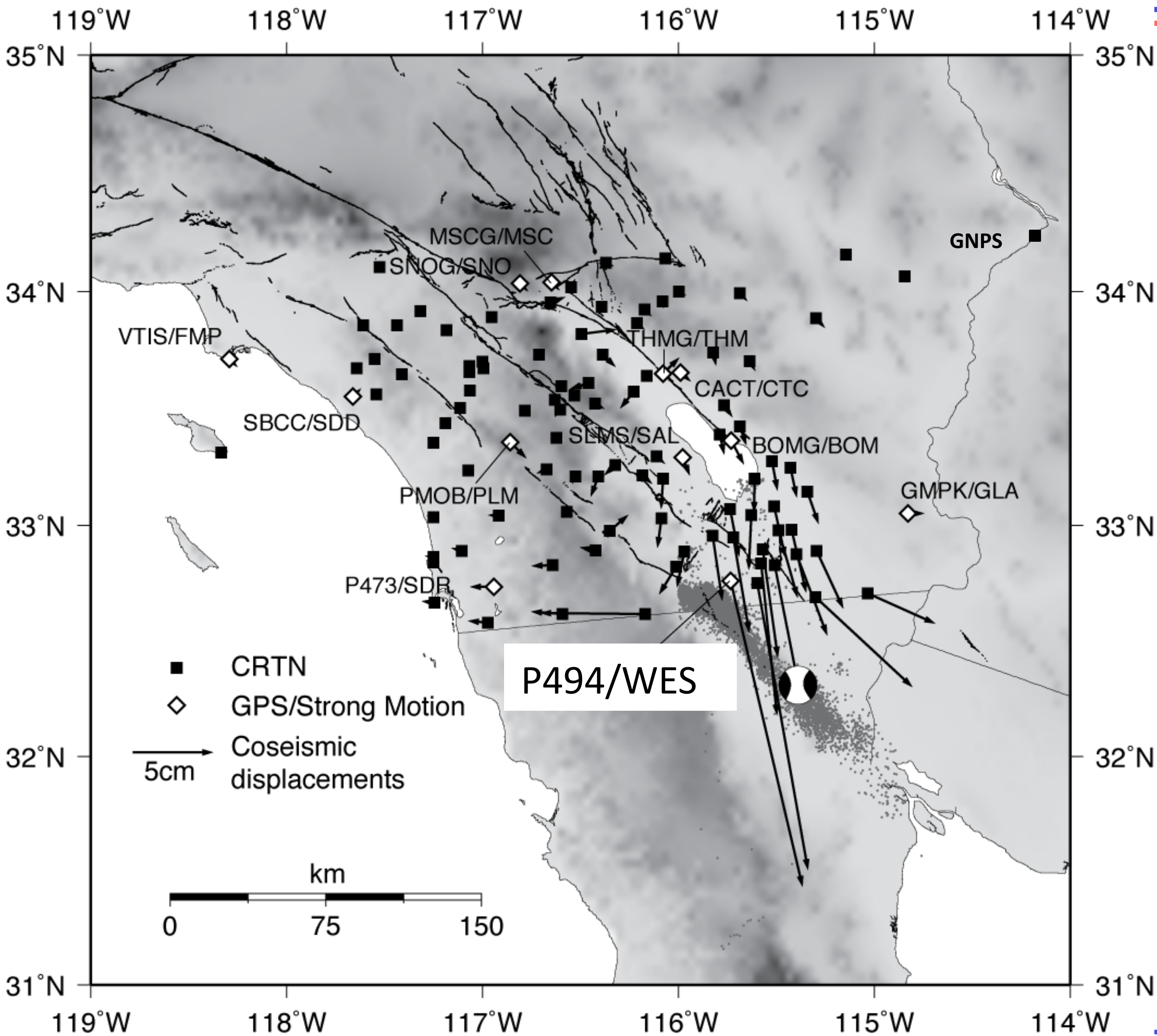
Courtesy H. Kanamori

Knowing that an Mw≈9 event has occurred near trench is critically important for recognizing an extraordinary emergency

Prototype EEW System Developed by AIST Project



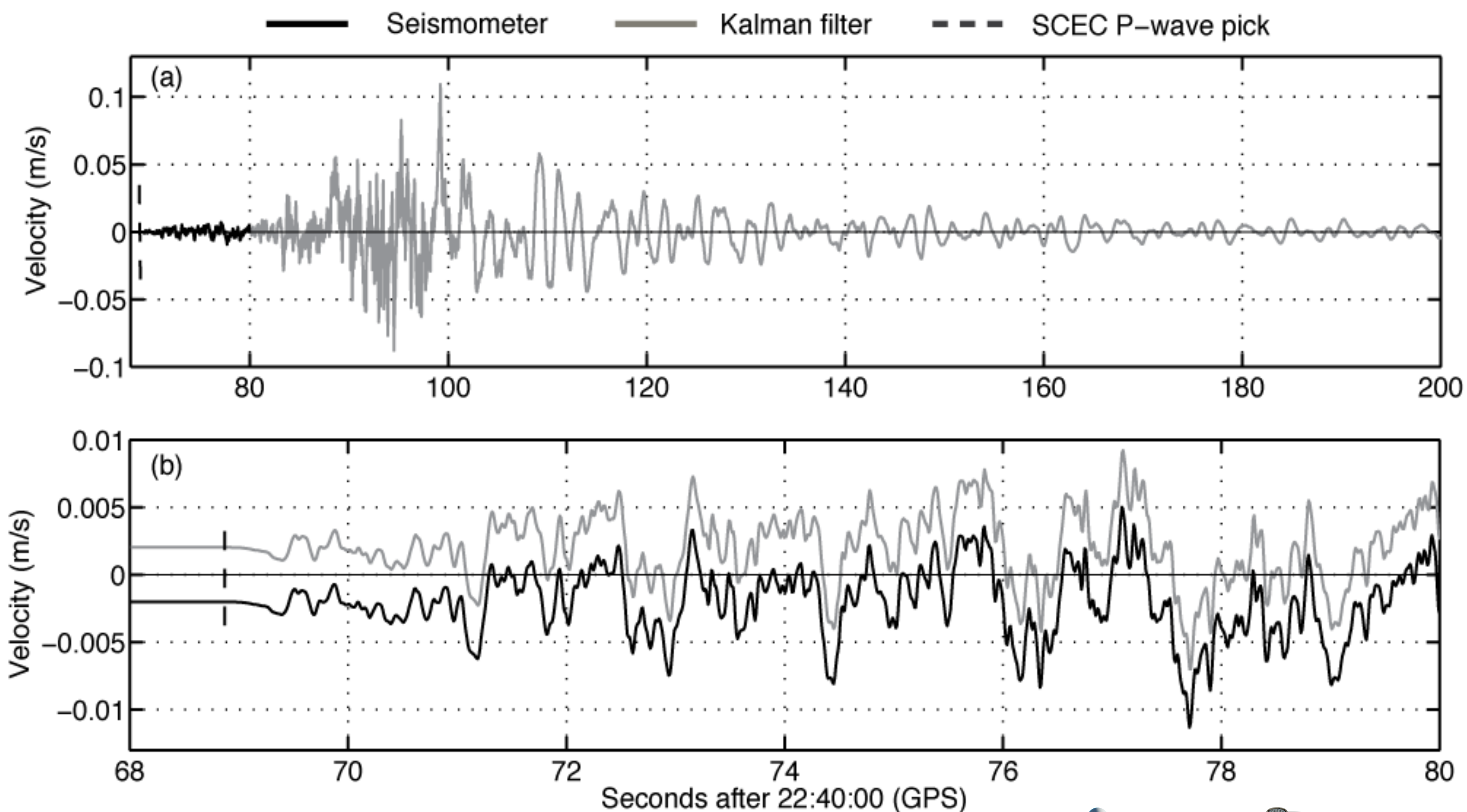
April 4, 2010 Mw 7.2 El Mayor-Cucapah Earthquake in Northern Baja California



- **105 1 Hz CRTN stations recorded the earthquake in southern California**
- **Using a Kalman smoother with a 2-3 s lag we estimated 100 Hz displacements using 1 Hz GPS and 100 Hz accelerometer data from 12 collocated GPS/ seismic stations**

1 Hz **+** **100 Hz**

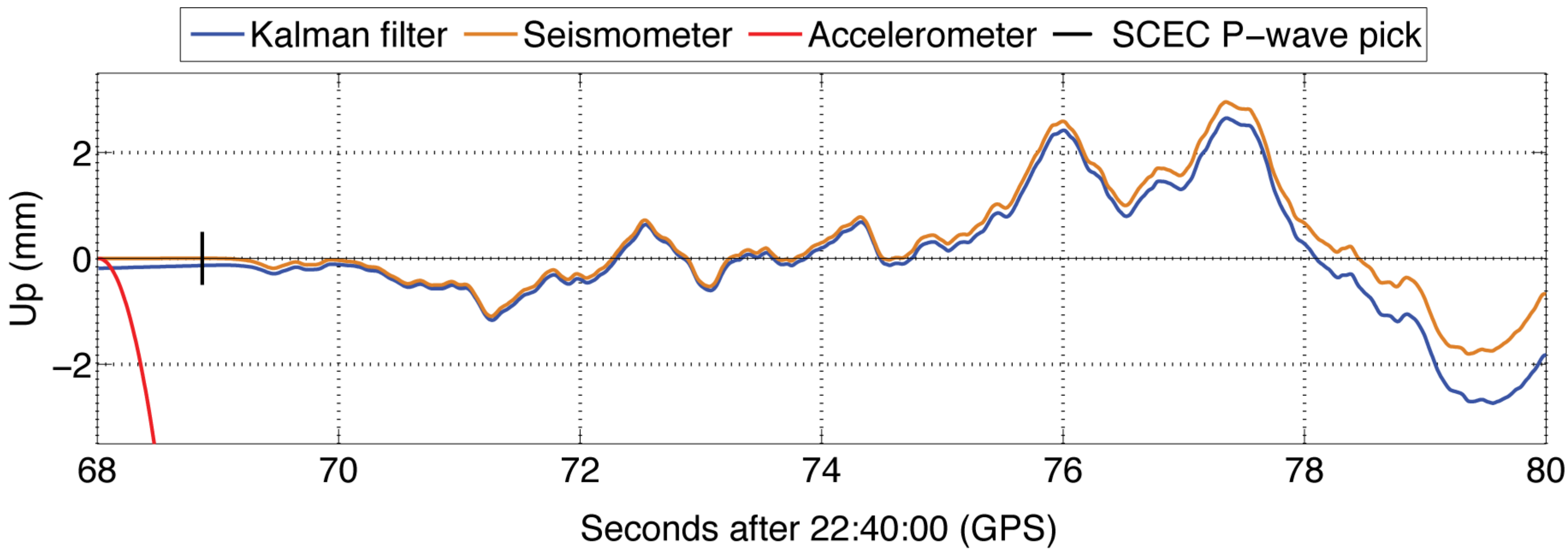
Real Time Estimation of Seismic Velocities: Detection of P-wave in Vertical Component at P494/WES



2010 Mw 7.2 El Mayor-Cucapah Earthquake

100 Hz

Real Time Estimation of Displacements: Detection of P-wave in Vertical Component at P494/ WES



The magnitudes and precision are on the order of 1-2 mm. Not possible to do this with only GPS observations because of poorer determination of vertical component.

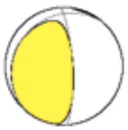
2010 Mw 7.2 El Mayor-Cucapah Earthquake

+

100 Hz

The first 90 minutes after the Tohoku-oki earthquake

Centroid locations vary by about 2°; earliest solution is 20 min after onset time



20min after O.T: USGS Internal W phase solution (6 channels)
Mw=9.0
Centroid loc.: Lat= 36.82N; Lon= 142.87E; Dep= 24.4 km
Time delay = Half duration = 68.7 sec
Best Double Couple: M0=3.941E+29 dyn.cm
NP1: Strike=222.7 ; Dip=16.8 ; Slip=134.6
NP2: Strike=356.8 ; Dip=78.1 ; Slip=78.0

22min after O.T: PTWC Automatic W phase solution (29 channels)
Mw=8.8
Centroid loc.: Lat= 39.00N; Lon= 142.80E; Dep= 83.5 km
Time delay = Half duration = 56.0 sec
Best Double Couple: M0=1.934E+29 dyn.cm
NP1: Strike=165.4 ; Dip=10.3 ; Slip=55.3
NP2: Strike=20.5; Dip=81.6 ; Slip=95.9

30min after O.T.: PTWC Automatic W phase solution (74 channels)
Mw=8.8
Centroid loc.: Lat= 38.30N; Lon= 143.50E; Dep= 83.5 km
Time delay = Half duration = 68.0 sec
Best Double Couple: M0=1.775E+29 dyn.cm
NP1: Strike=194.3 ; Dip=22.8 ; Slip=81.3
NP2: Strike=23.7 ; Dip=67.5 ; Slip=93.6

40min after O.T.: PTWC Manual W phase solution (105 channels)
Mw=9.0
Centroid loc.: Lat= 38.40N; Lon= 142.90E; Dep= 24.4 km
Time delay = Half duration = 69.0 sec
Best Double Couple: M0=4.325E+29 dyn.cm
NP1: Strike=190.6 ; Dip=11.1 ; Slip=76.7
NP2: Strike=24.2 ; Dip=79.1 ; Slip=92.6

48min after O.T: USGS Internal W phase solution (74 channels)
Mw=8.9
Centroid loc.: Lat= 37.82N; Lon= 142.87E; Dep= 24.4 km
Time delay = Half duration = 72.2 sec
Best Double Couple: M0=3.225E+29 dyn.cm
NP1: Strike=204.4 ; Dip=14.8 ; Slip=104.3
NP2: Strike=9.7 ; Dip=75.7 ; Slip=86.3

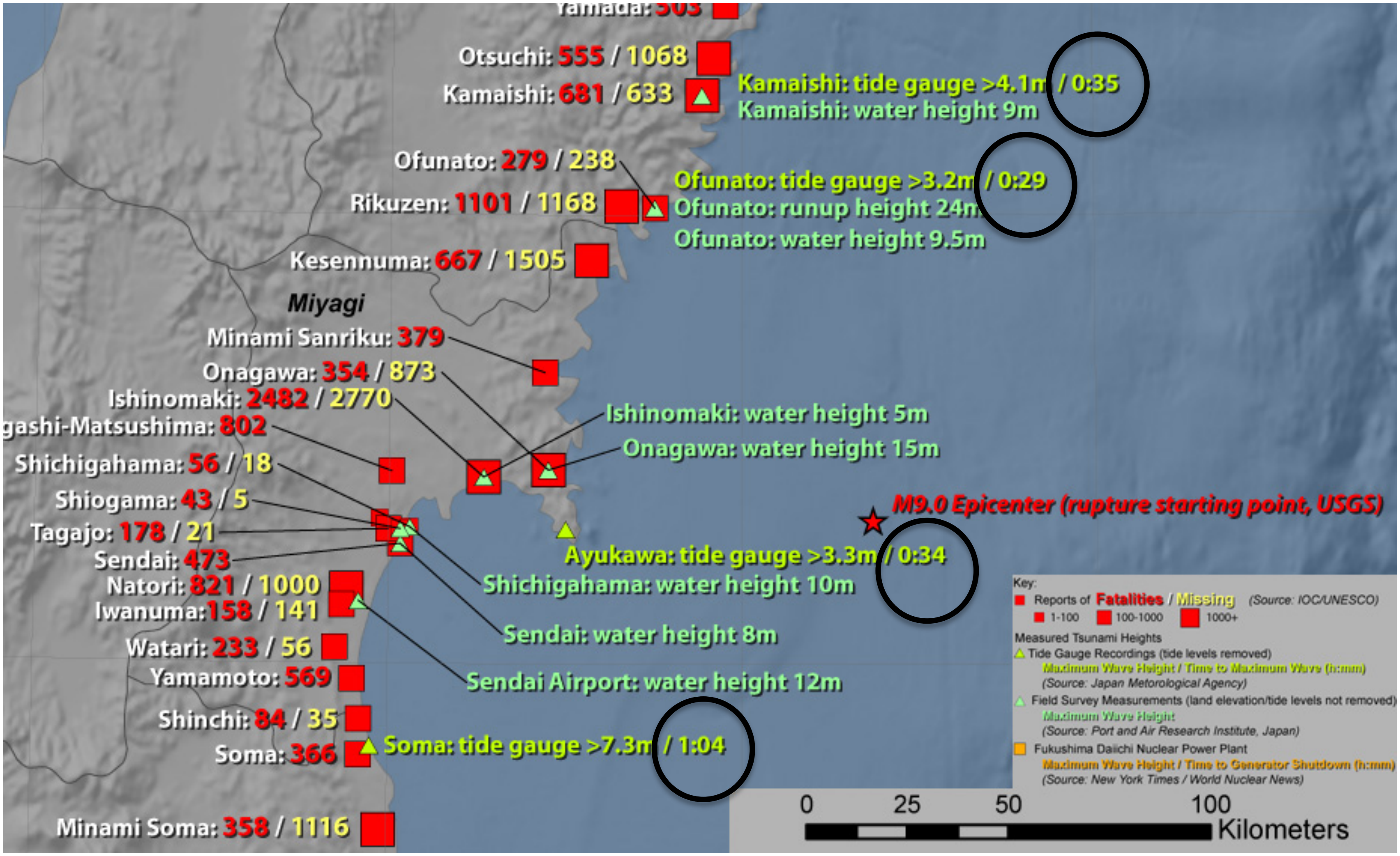
1hour after O.T.: USGS Published W phase solution (89 channels)
Mw=8.9
Centroid loc.: Lat= 38.32N; Lon= 141.77E; Dep= 24.4 km
Time delay = Half duration = 48.0 sec
Best Double Couple: M0=2.836E+29 dyn.cm
NP1: Strike=162.0 ; Dip=16.9 ; Slip=45.1
NP2: Strike=28.2 ; Dip=78.1 ; Slip=102.1

1hour 30min after O.T.: IPGS W phase solution (146 channels)
Mw=9.0
Centroid loc.: Lat= 38.12N; Lon= 142.97E; Dep= 24.4 km
Time delay = Half duration = 72.0 sec
Best Double Couple: M0=3.507E+29 dyn.cm
NP1: Strike=196.3 ; Dip=14.4 ; Slip=85.1
NP2: Strike=21.4 ; Dip=75.7 ; Slip=91.3

Rapid detection of CMT has important implications for timely tsunami warning

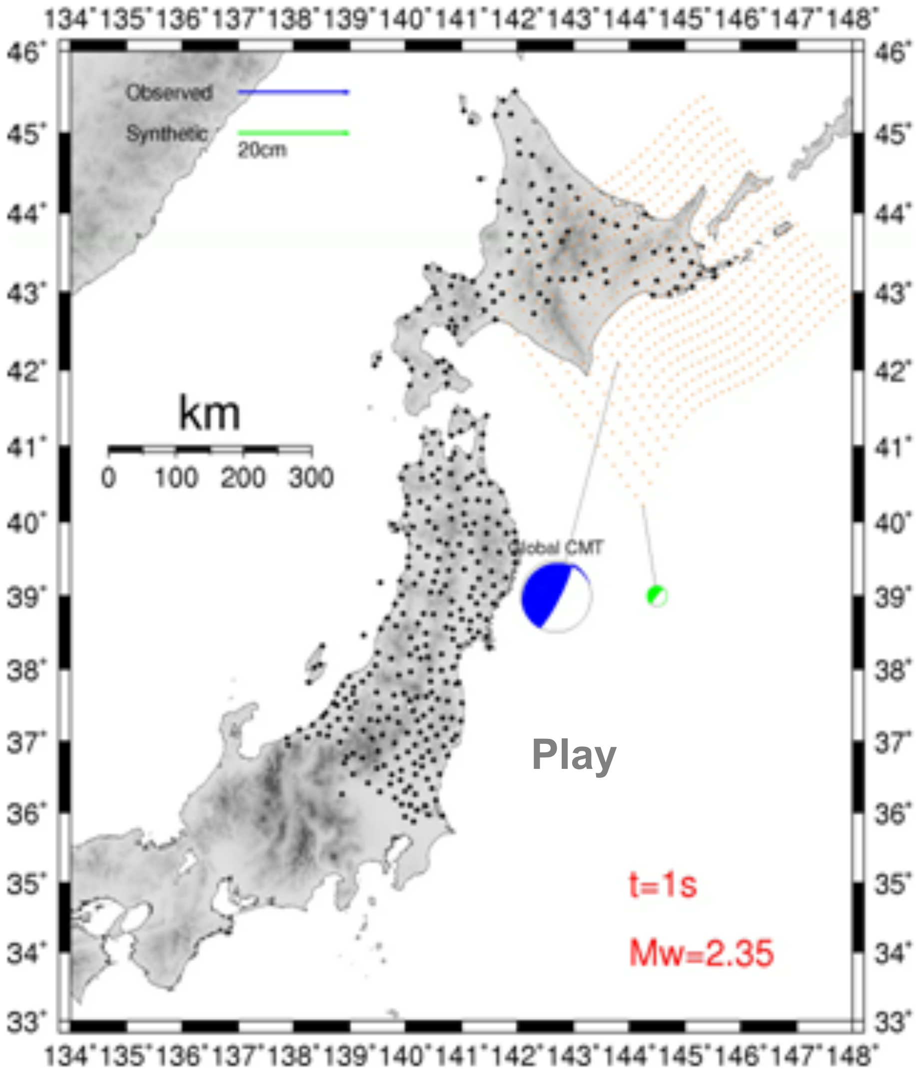
http://eost.u-strasbg.fr/wphase/events/tohoku_oki_2011/

Tsunami Travel Times for Tohoku-oki



http://www.ngdc.noaa.gov

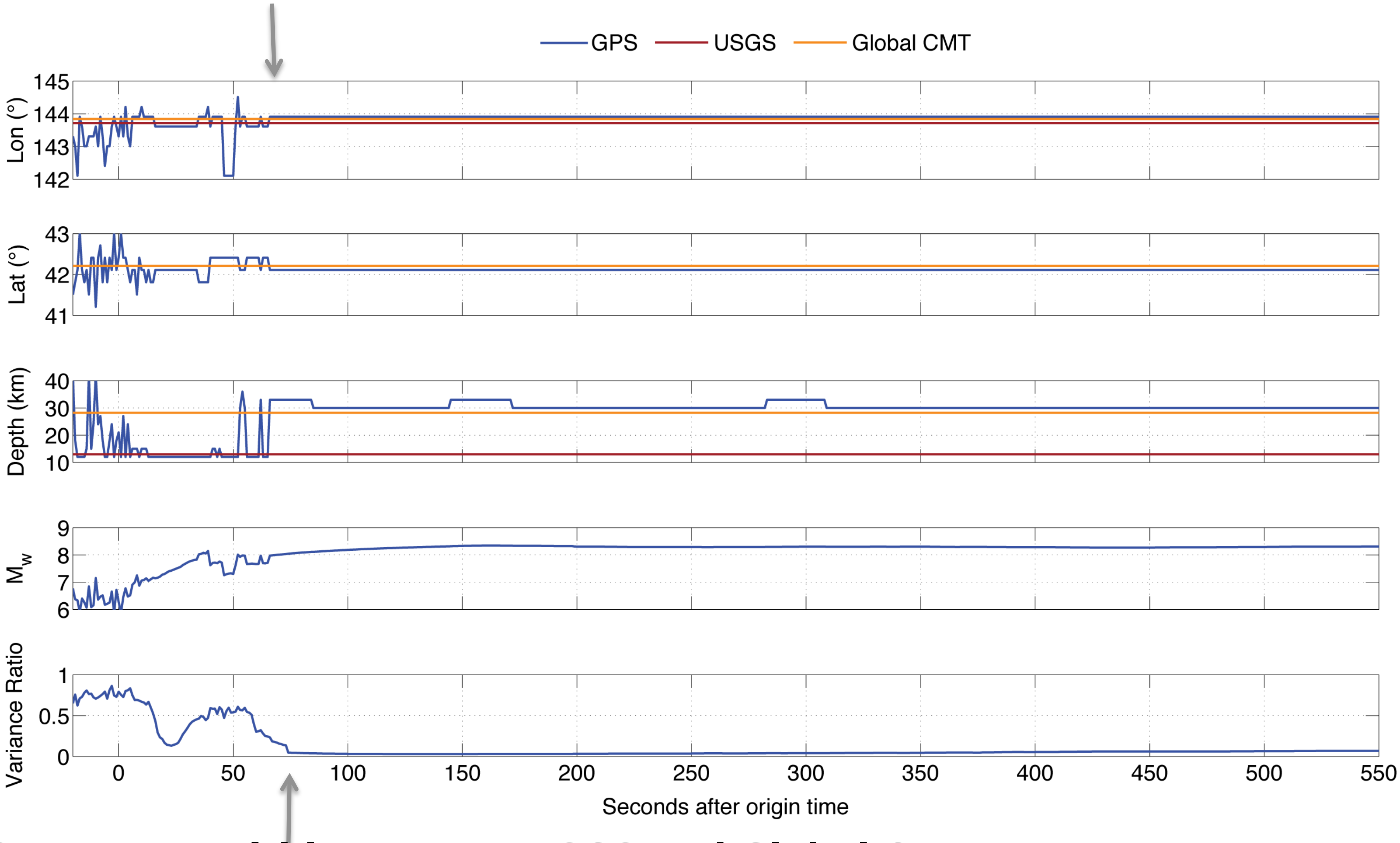
Rapid Estimation of Centroid & Magnitude 2003 Mw 8.3 Tokachi-oki Earthquake



Our geodetic determination of centroid moment tensor solution for 2003 Mw 8.3 Tokachi-oki earthquake from observed 1 Hz GPS data processed in a simulated real-time mode

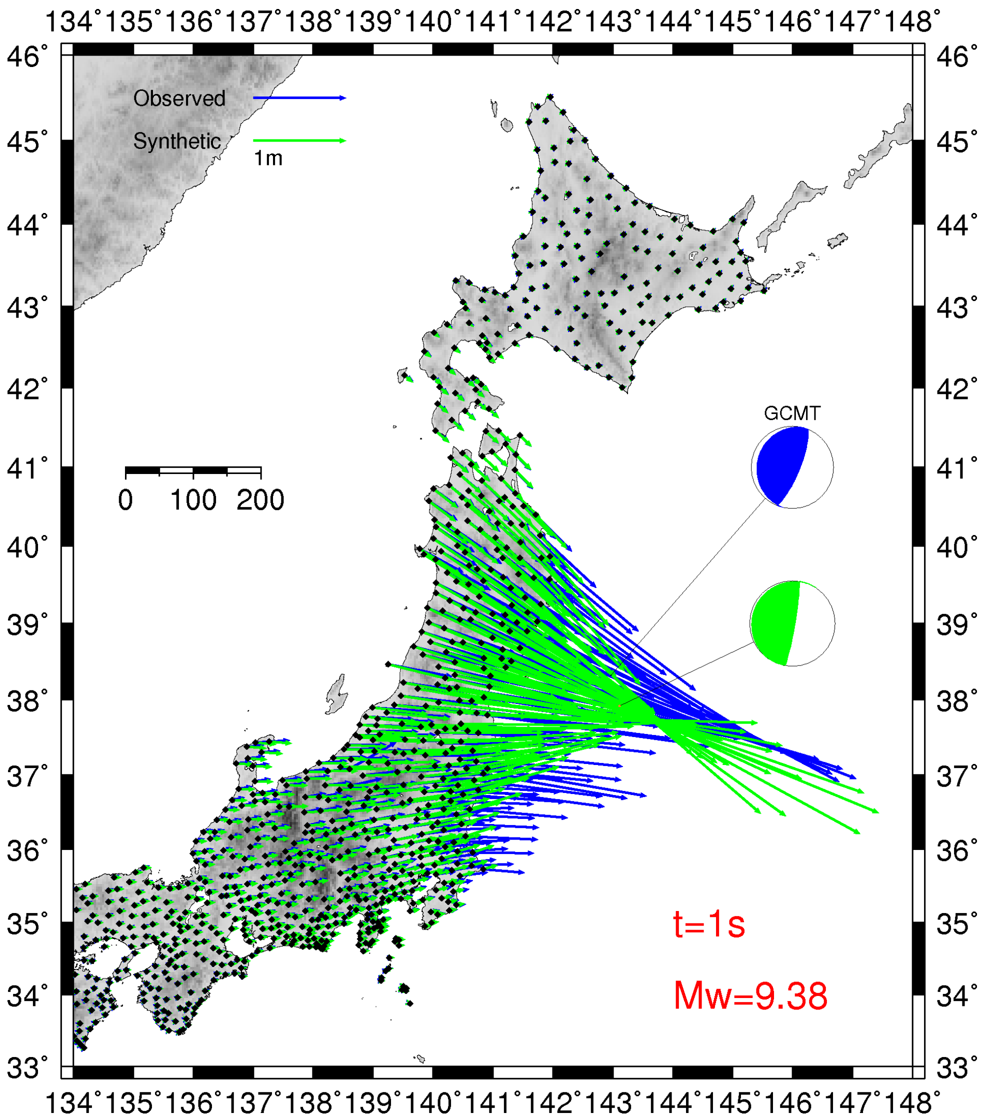
Grid search around epicenter, no a priori location

Rapid Estimation of Centroid & Magnitude
2003 Mw 8.3 Tokachi-oki Earthquake



Converges within ~ 75 s, USGS and Global CMT solutions shown for comparison

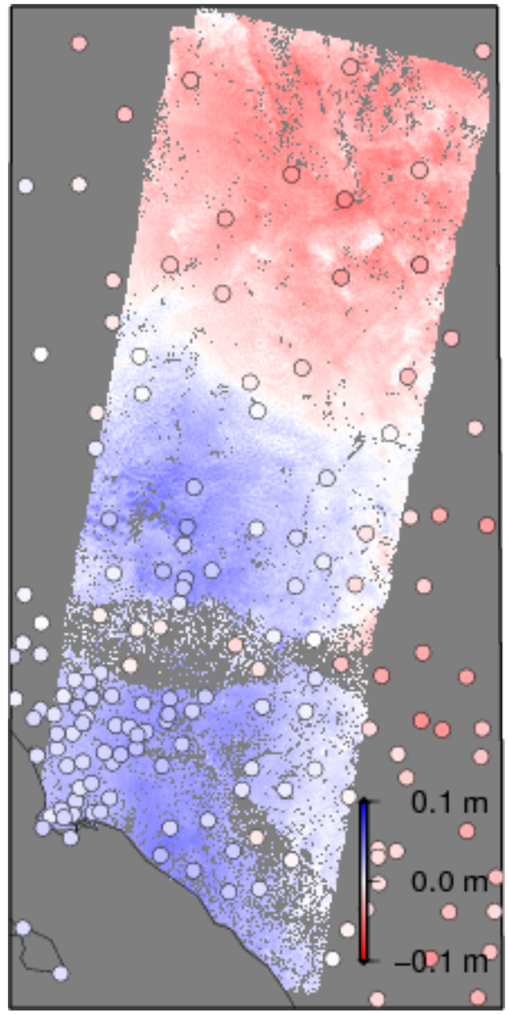
Tohoku-oki Single Epoch Inversion



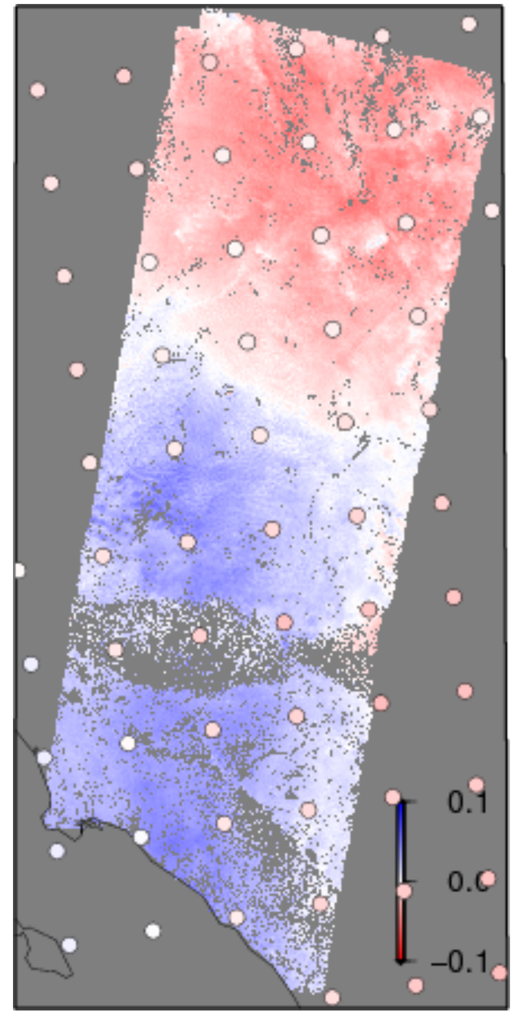
Our geodetic determination of centroid moment tensor solution for 2011 Mw 9.0 Tohoku-oki earthquake from coseismic displacements observed from one epoch of 30 s GPS data

Troposphere InSAR Calibration from In Situ GPS Networks

- Leverage GPS estimates of troposphere delay already routinely calculated by JPL and SIO
- Complement the GPS estimates' accuracy and temporal resolution with the spatial resolution of weather models
- Correction maps can reduce atmospheric noise in InSAR interferograms. Favorable results in tests on Envisat and ALOS interferograms



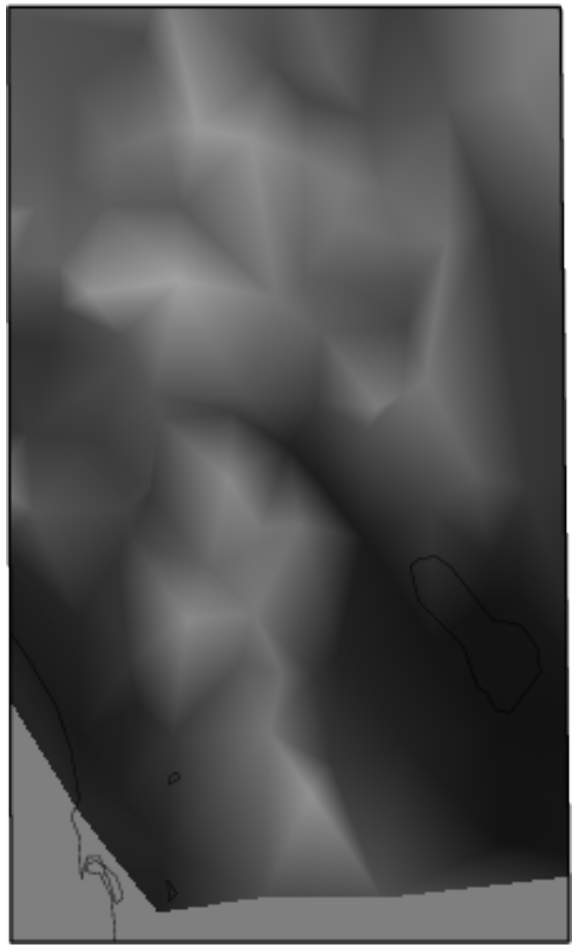
GPS



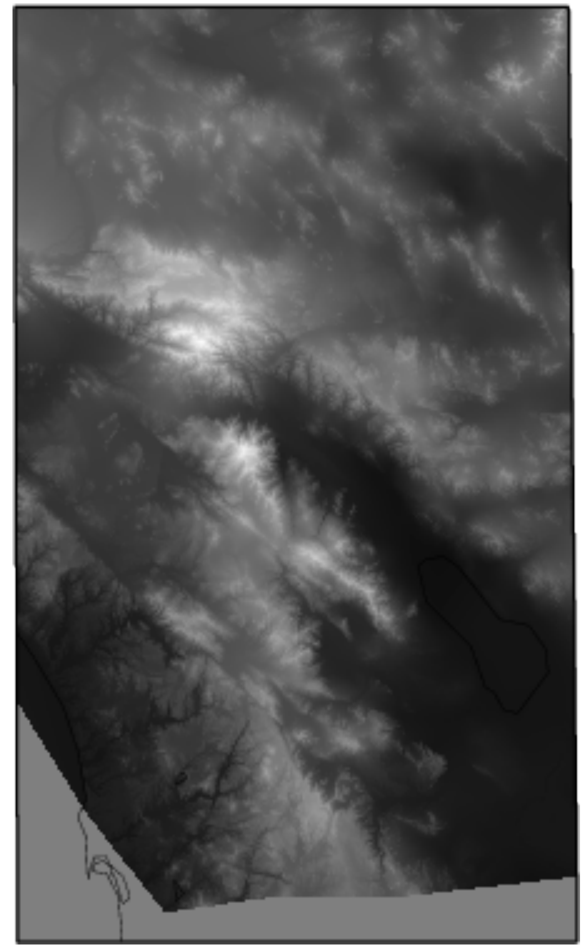
Weather model

Map formation, including topography

- **Scale troposphere delay estimates to sea level**
- **Interpolate on the sea level plane**
- **Use DEM to scale interpolated grid to terrain**



Correction map without DEM

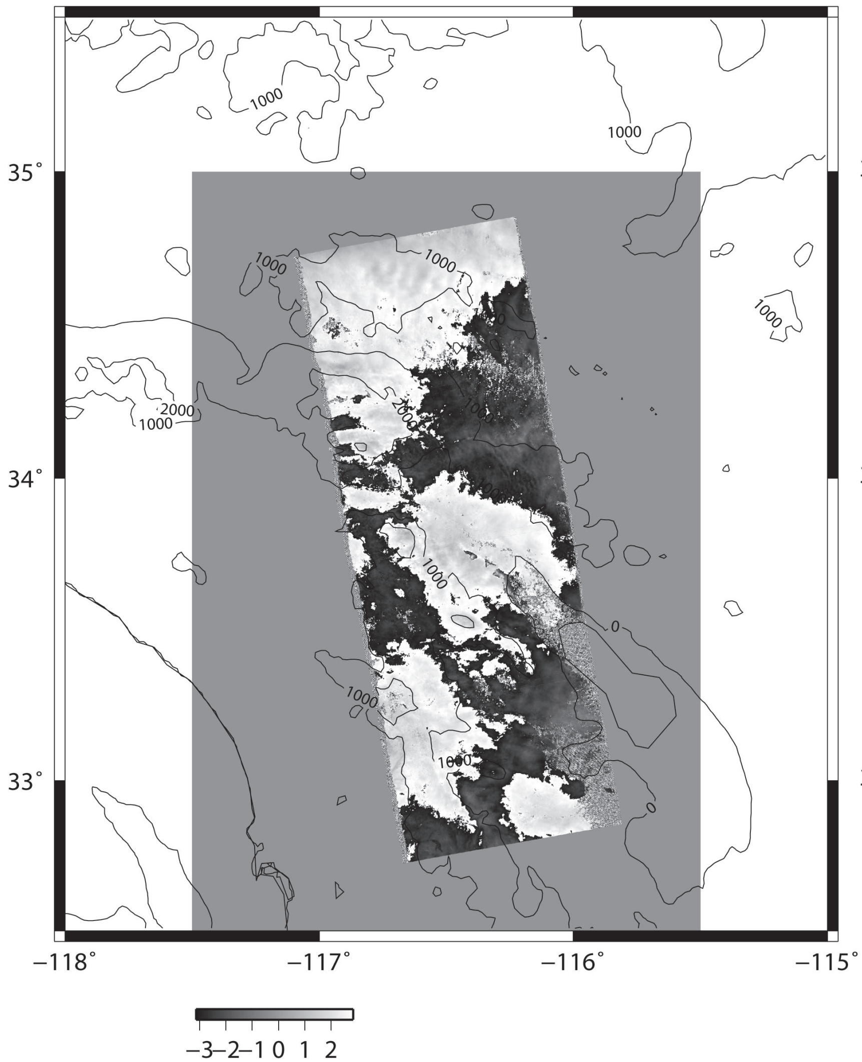


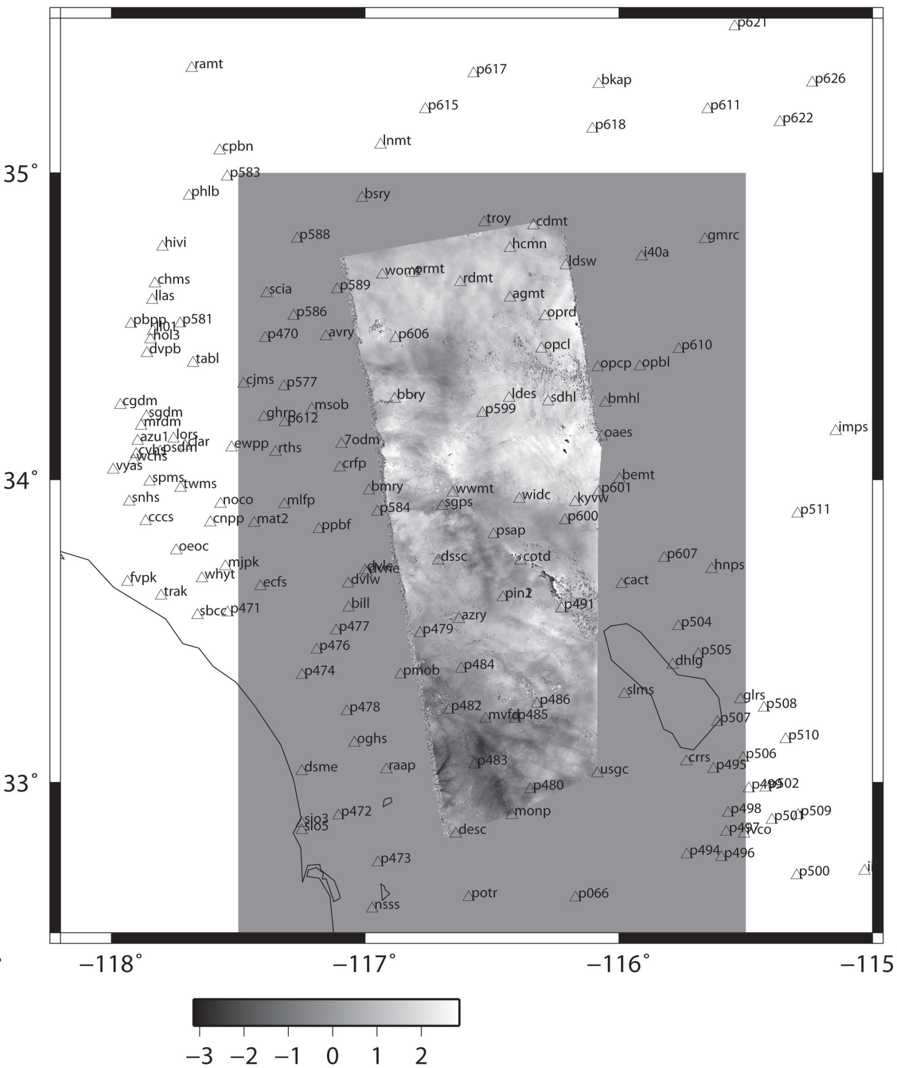
Correction map using DEM

Improvement in InSAR Processing

ph_04233_19666.ps

coph_04233_19666.topo.ps

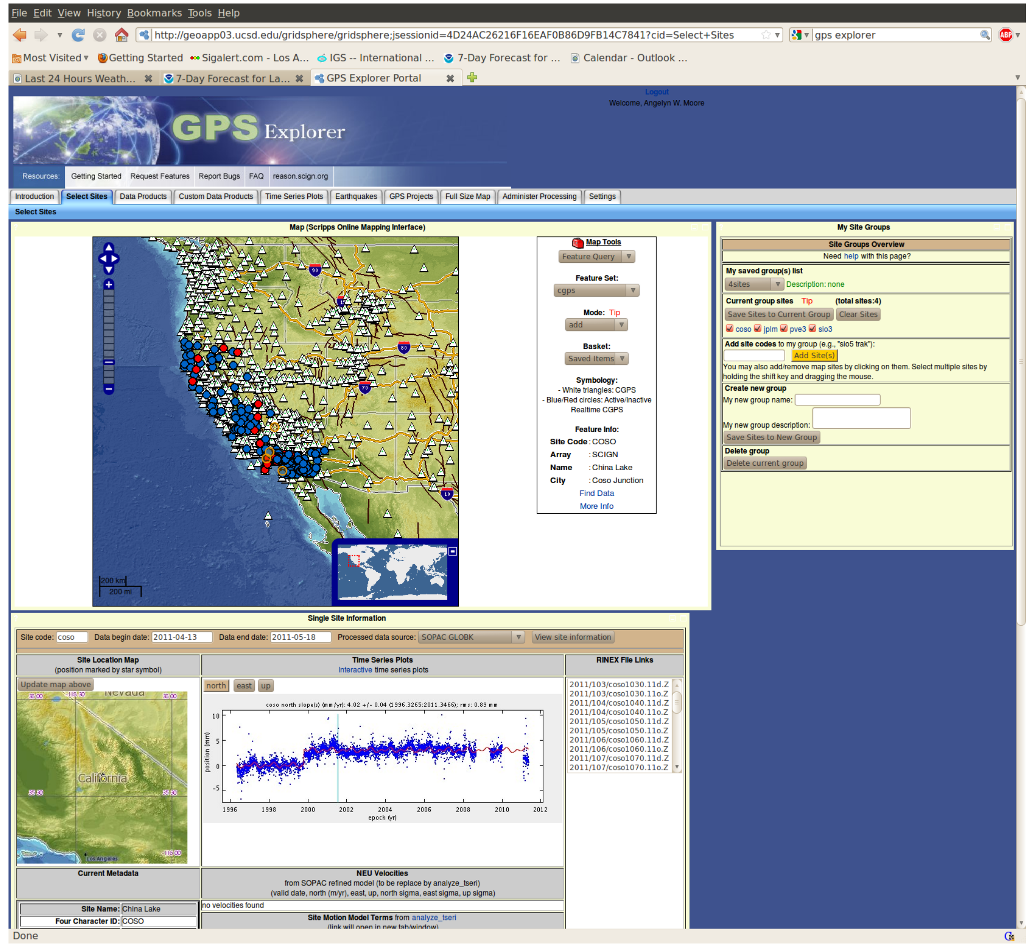




Produced by Xiaoteng Tong, SIO

Implementation into GPS Explorer Data Portal

- Correction maps to be offered through GPS Explorer
- User specifies spatial boundaries, date/time, and selection of modeling parameters
- System returns a correction map



http://geoapp03.ucsd.edu/gridsphere/gridsphere

Summary

Through AIST funding we have:

- **Developed elements of earthquake/tsunami early warning based on real-time 100 Hz mm-level broadband displacements from collocated 1 Hz GPS and 100 Hz accelerometer data**
- **Improved earthquake characterization time by an order of magnitude compared to seismic-only methods**
- **Introduced a new data source for detailed near-field modeling of large earthquake ruptures based on 3-D total displacement waveforms with mm-accuracy**
- **Demonstrated improved InSAR processing for deformation using troposphere maps from in situ GPS networks**
- **Begun implementing these capabilities through GPS Explorer Data Portal developed through NASA MEaSUREs project.**